AIRBORNE LIDAR AND AIRBORNE HYPERSPECTRAL IMAGERY: A FUSION OF TWO PROVEN SENSORS FOR IMPROVED HYDROGRAPHIC SURVEYING

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Airborne lidar has become a fully operational tool for hydrographic surveying in recent years. Currently there are four airborne laser bathymetry (ALB) systems operating worldwide. One system, the U.S. Army Corps of Engineers Scanning Hydrographic Operational Airborne Lidar Survey (SHOALS) simultaneously measures water depth and adjacent surface topography.

Airborne hyperspectral imagery from the Compact Airborne Spectrographic Imager (CASI) has been proven to be a valuable tool for coastal measurements and analysis. CASI's spectral resolution of 288 bands for each spatial pixel allows for the extraction of a vast amount of information such as water clarity, water temperature, bottom type, bathymetry, as well as water quality (chlorophyll, dissolved organic carbon, and suspended minerals), soil types, and plant species.

In order for ALB to achieve a comprehensive hydrographic capability, additional sensors would have to be integrated. Combining SHOALS and CASI would be a substantial step in accomplishing a full hydrographic survey capability for ALB.

Surveys using this combination of sensors will provide valuable information for different agencies. The U.S. Army Corps of Engineers needs information that will aid in sediment transport monitoring and regional sediment management. The Naval Oceanographic Office (NAVOCEANO) uses the ALB system to collect hydrographic information about the littoral zone for the warfighter. By adding the hyperspectral capability, NAVOCEANO may be able to enhance its ability to quickly provide a more complete environmental picture.

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INTRODUCTION

The last decade of the 20th century saw some exciting changes in the way we view hydrographic surveying. Many changes came with the acceptance of multibeam echo sounders in addition to the single-beam echo sounder to collect soundings. Digital sidescan recorders have also advanced the technology and made the collection of data more efficient. One of the changes involved the use of Airborne Lidar Bathymetry (ALB). Another change was the ability to collect remotely sensed environmental data in nearshore regions from airborne and satellite-borne sensors. In addition to accurate bathymetry, the delineation and identification of bottom sediments (sand, mud, sea grass, coral, etc.) are part of the hydrographic survey process.

Table 1. Hydrographic survey objectives.

bathymetry
navigation hazards
Identification of bottom type
Physical properties of water (expendable bathythermographs (XBTs), conductivity, temperature and depth recorder (CTDs), optical properties)
currents and tides
position of navigation aid and buoys

HYDROGRAPHIC SURVEY METHODS

Hydrography has been defined as surveying of a water area, with depth measurement as the primary focus. However, the survey is not complete until there has been an analysis and scientific description of other physical conditions (Table 1) such as tides, currents, shoreline conditions, bottom composition, and determination of the physical and chemical properties of water, as well as positioning hazards and aids to navigation (U.S. Department of Commerce, 1976). A principal objective is to obtain information on water areas and adjacent coastal regions that will serve as source material for Navy and commercial fleet support; in addition, nautical charts, coastal engineering design studies, sailing directions and coastal pilots, and other nautical combinations will be of value to the user. Recent technological improvements in the area of surface and sub-surface data collection have given the hydrographer a number of sophisticated tools necessary to collect a wide range of data used in producing today's charts, as well as to provide a reliable database for electronic navigation of tomorrow. In spite of the new advancements, surface and sub-surface hydrographic surveys remain costly and time consuming.

Fig. 1. Typical method of personnel preparing to launch a grab sampler.

Many of the ancillary processes require that the bathymetry data collection effort be halted in order to collect other data. Determining bottom composition is an example of this process. Currently, it is necessary to establish a preliminary grid for sampling based on charted information and prepare a team with the proper gear to successfully

gather, identify, catalog, and store the samples. Typically, the vessel navigates to a specified location represented by the planned grid; then the particular bottom sample instrument is deployed (Figure 1). The instrument is lowered and raised until a sample is obtained. If no sample is obtained after several attempts, it is assumed that the bottom is "hard" and is recorded as such for that location. (This method was adequate for the general purposes of collecting anchorage information.) The vessel then moves to the next grid location and repeats the process. As the data collection progresses, the data are reviewed, and adjustments are made to the grid pattern in an effort to identify various bottom composition zones. Today, the typical customer of hydrographic products requires a more comprehensive understanding of the seabed. Recognizing the limitations of this spot data collection, advancements have been directed to successfully correlate sonic signal patterns to specific bottom composition. Although some ground truth bottom samples (using traditional methods) are necessary, employing digital methods of determining bottom composition has increased surface and sub-surface data collection efficiency and greatly improved the product that can be generated.

The advent of ALB has provided a means to substantially reduce the cost and time needed to collect depth data in the littoral region. Unfortunately, many of the data types needed to generate today's sophisticated products require the deployment of surface platform instruments. In order for ALB to achieve full hydrographic capability, employing a combination of additional sensors may be necessary.

AIRBORNE LIDAR BATHYMETRY (ALB)

An ALB uses lidar technology to measure water depths. A laser transmitter/receiver (transceiver) mounted on an aircraft transmits a laser pulse which travels to the air-water interface, where a portion of this energy reflects back to the receiver (Guenther et al., 1996). The remaining energy propagates through the water column and reflects off the sea bottom. The water depth measurement comes directly from the time lapse between the surface return and bottom return, and each sounding is appropriately corrected for surface waves and water level fluctuations (Figure 2). In practical application of this technology, laser energy is lost due to refraction, scattering, and absorption at the water surface, sea bottom, and as the pulse travels through the water column. The combination of these effects limits the strength of the bottom return and therefore limits the maximum detectable depth. Optical water clarity and bottom types are the two most limiting factors for depth detection. Typically, lidar bathymeters collect through depths equal to three times the site’s Secchi (visible) depth.

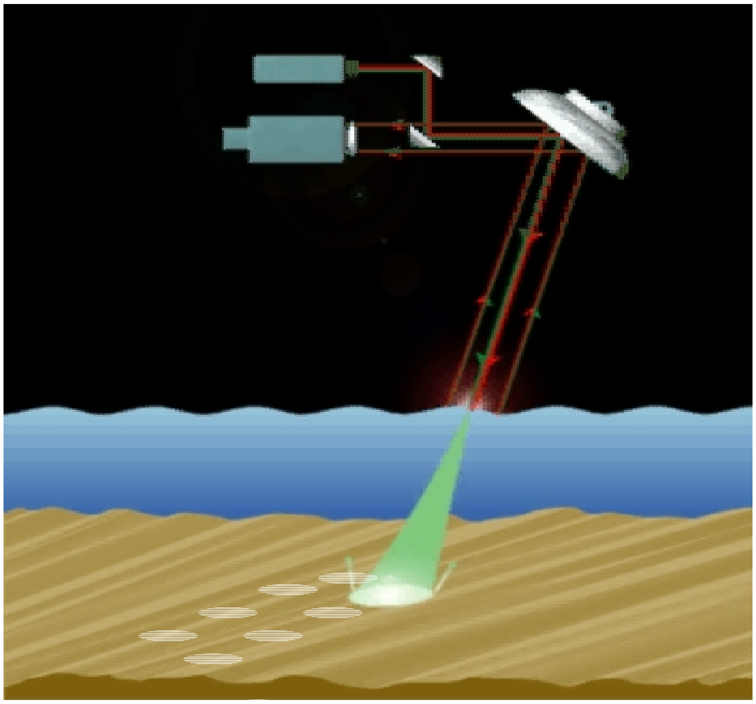

Fig. 2. ALB operating principle. Infrared energy travels to water surface, and blue green energy travels through water column.

THE SCANNING HYDROGRAPHIC OPERATIONAL AIRBORNE LIDAR SURVEY (SHOALS) SYSTEM

The SHOALS system uses a scanning, pulsed, infrared (1064 nm), and blue-green (532 nm) laser transmitter with five receiver channels mounted on either a Bell 212 helicopter, a fixed-wing Twin Otter, or other equivalent aircraft of opportunity (Figure 3). Infrared and blue-green frequencies were selected to optimize air-water interface detection and water penetration, respectively. Typically, SHOALS operates at an altitude of 300-400 m and a speed of 60 m/s, giving a survey swath width of 110 m and a horizontal spot density of 4 m. SHOALS survey rate is nominally 16km^2 per hour, thus, is several orders of magnitude faster than conventional swath-fathometer survey rates. Two receiver channels record energy vs. time (waveforms) for each reflected blue-green pulse and two channels record waveforms for each reflected infrared pulse. The fifth channel records a red Raman (645 nm) energy that results from excitation of the surface water molecules by the blue-green laser energy. SHOALS uses the two blue-green waveforms to determine the bottom interface, where one waveform is for shallower depths, and the other is for deeper depths to 40 m. To avoid problems associated with air-water interface detection, SHOALS uses any of two waveforms to determine this interface accurately. Prioritized by order of use these are the Raman then infrared channels. The second infrared channel is used in conjunction with the first to discriminate between land and water returns. In response to the U.S. Army Corps of Engineers' (USACE's) need to map the upland beach, dunes, and above-water portion of coastal structures, SHOALS was modified in 1996 to include topographic capabilities. Unlike most topographic lidar systems, which use an infrared frequency, SHOALS uses its blue-green frequency to measure topographic elevations.

Fig. 3. The SHOALS system. Counterclockwise from left are SHOALS mounted inside a Twin Otter, the SHOALS transceiver, and the SHOALS operator's console.

SHOALS positioning comes either from differential global positioning system (DGPS) provided by U.S. Coast Guard beacons and OMNISTAR satellite system or from kinematic GPS (KGPS) provided by local stations. When SHOALS operates with DGPS, which provides horizontal aircraft position, horizontal and vertical accuracy are ±3 m and ±15 cm, respectively. When SHOALS operates with KGPS, which additionally provides vertical aircraft position, horizontal accuracy improves to ±1 m. An inertial reference system mounted with the laser optics accounts for aircraft motion effects.

Data collected with SHOALS meets USACE Class 1 and International Hydrographic Organization (IHO) Order 1 standards. Through independent testing, both the U.S. National Ocean Service and U.S. Navy verified that SHOALS met IHO charting standards (Riley, 1995). Additionally, the USACE conducted extensive field tests to ensure that SHOALS met their Class 1 survey standards, which are more restrictive than the IHO standards. Table 2 summarizes SHOALS current performance characteristics.

Table 2. SHOALS performance characteristics.	
Maximum Depth	to 40 m
Vertical Accuracy	±15 cm
Horizontal Accuracy	
DGPS	±3 m
On-The-Fly (OTF) KGPS	±1 m
Sounding Density	4-m grid (variable)
Operating Altitude	300 m (variable)
Scan Swath Width	110 m (variable)
Operating Speed	60 to 120 m/s

HYPERSPECTRAL SENSORS

Tremendous development in the field of remote sensing has taken place in the past decades. No one area of remote sensing has had as much impact for environmental studies as imaging spectrometry (Lewotsky, 1994). Imaging spectrometers or hyperspectral sensors, in reference to the multispectral character of the data set, collect images of a scene and provide access to several tens to hundreds of very narrow spectral channels nearly simultaneously (Lewotsky, 1994; Kerekes, 1995; and Estep et al., 1994).

Imaging spectrometers are passive sensors that measure reflected sunlight from objects on the earth's surface (Figure 4). All objects have unique spectral footprints that can register in wavelengths, or bands, invisible to the human eye. Hyperspectral imaging sensors operating across hundreds of wavelengths allow this hidden world to be revealed (Terrie, 1995, and Lewotsky, 1994).

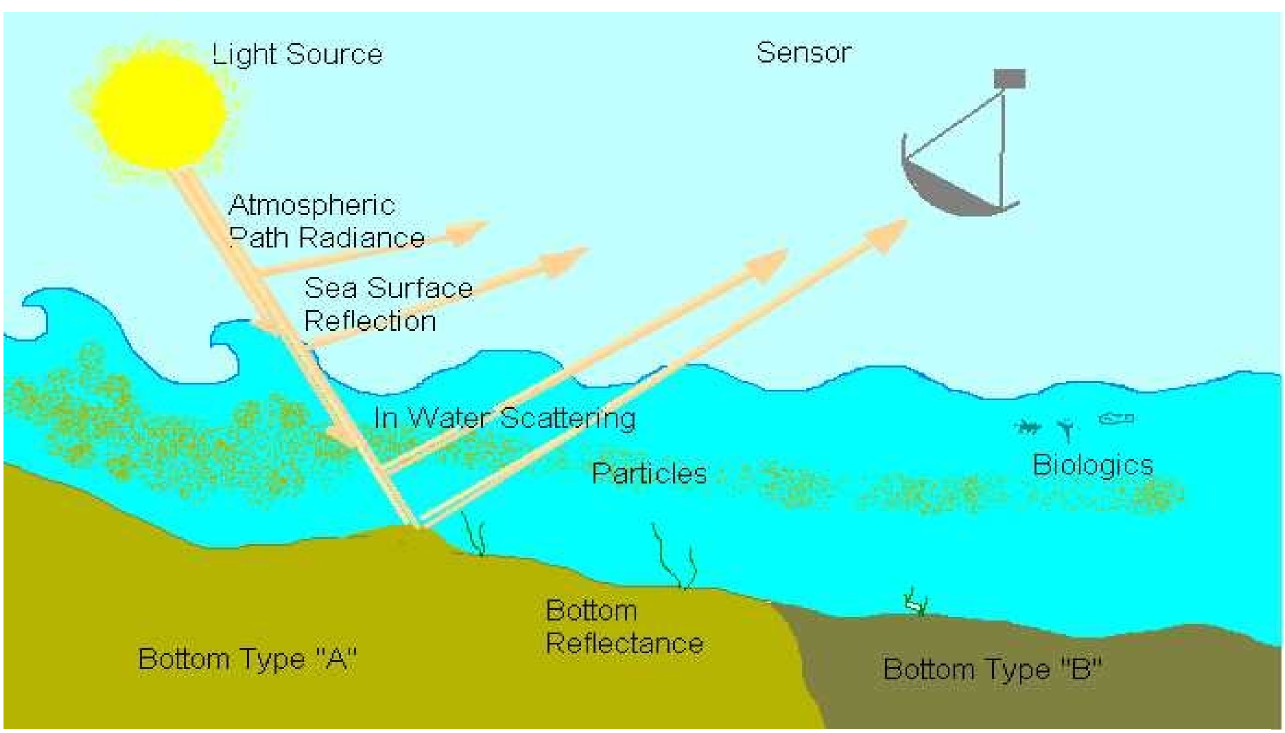

Fig. 4 Coastal Optics (Adapted from Terrie, 1995).

These finely tuned sensors are coupled with powerful processing algorithms that remove from the remote signatures the contributions due to (1) sea-surface glint, (2) atmosphere, (3) water column radiance and, (4) propagation of bottom reflectance to the surface. When combined with in-situ measurements of inherent optical properties, solution for the bottom reflectance using these techniques can be allowed (Durey et al., 1997).

A commonly cited problem with remote sensing of underwater environments is the confusing effect of variable depth on bottom reflectance. Examples are the similarity of sand and seagrass at some depth such as 3 m. However, a model developed by Lyzenga (1978) compensates for variation in depth by assuming that light attenuation follows an exponential decay curve as depth increases in clear water (Mumby et al., 1998). (Readers are directed to Lyzenga's papers for further details.) Estep et al. (1994) suggest a technique to use SHOALS water optical information (a system attenuation coefficient or ksys) and depth information to compute the diffuse optical depth at each calibrated point in an image. A direct computation of the in-situ spectral bottom reflectance can be obtained after modeling the water reflectance. The lack of reliable high-resolution data in coastal waters has hampered the development of coastal optics models based on in-situ measurements of bottom spectral reflectance (Terrie, 1995). However, programs such as the one being developed in the Coastal Benthic Optical Properties (CoBOP) program at the Office of Naval Research (ONR) will greatly enhance the ability to rapidly characterize shallow marine environments with hyperspectral remote sensors. Analysis of marine spectral data is more challenging than geologic or vegetative areas. Due to the exponential increase in light attenuation in red wavelengths, most ocean optics research has been limited to the visible spectrum in the 400-nm to 700-nm range. Only 2-7% of in water targets are reflected contrasted with the 10-50% of land targets.

The Airborne Visible-Infrared Imaging Spectrometer (AVIRIS) is one airborne sensor, originally intended for use over land, which has been used to study the coastal marine environment. Previous work done by Hamilton et al. (1993) on chlorophyll content estimation at Lake Tahoe with the AVIRIS sensor has shown that the clear waters of Lake Tahoe are as clear as the clearest ocean waters, so results were good, but not elsewhere (Terrie, 1995). At the time that AVIRIS was flown, it was noted that it lacked the signal-to-noise ration (SNR) in the blue portion of the spectrum. Blue and green wavelengths have greater penetration into water, which is useful for bottom sediment identification. Another problem cited in Terrie's paper (1995) was upwelling light. At the time his paper was written there were no reliable procedures developed to deal with that problem. Work done by Carder et al. (1993) showed that AVIRIS data compared well with in-situ measurements after post-flight recalibration to improve the sensor sensitivity in the shorter wavelengths. The same problem was stated with the Compact Airborne Spectrographic Imager (CASI) in Terrie's work (1995) off Florida. Enhancements in CASI should remedy that problem. Other airborne hyperspectral sensors such as Advanced Airborne Hyperspectral Imaging System (AAHIS) and Digital Airborne Imaging Scanner (DAIS) have been used in the study of the marine environment as well, but the primary focus of most studies has been biologic (coral mapping, chlorophyll estimates and identification of other marine vegetation).

COMPACT AIRBORNE SPECTROGRAPHIC IMAGER (CASI)

ITRES Research Limited of Canada produced the CASI, a pushbroom scanner which is one of 19 or more known airborne hyperspectral sensors. Pushbroom scanners collect imagery by scanning a line at a time, perpendicular to the motion of the aircraft (across track). An image is formed when the forward motion of the aircraft allows the sensor to sweep a swath of data along the track (Terrie, 1995). Two different modes of operation are available for CASI: spatial and spectral. Unfortunately, they cannot be operated simultaneously. Spatial resolution of CASI varies with altitude, airspeed, and sensor integration or exposure time. Spatial resampling of the data is required in order to obtain square pixels, since the along track and across track resolutions are not generally the same (Terrie, 1995). This sensor offers imaging capabilities in 288 contiguous spectral bands in the range from 0.4-0.87 m, with an average spectral resolution of 3 nm (Lewotsky, 1994). The spectral range which is of primary importance for oceanographic communities is between 400 nm and 700 nm (Terrie, 1995). Although other systems may offer similar sensor characteristics, the compact, lightweight, and portable design of CASI makes it a good choice for fusion with the SHOALS system. It can be flown on a variety of aircraft at altitudes from 1,100-10,000 ft (335-3048 m).

The Borstad CASI (Figure 5) covers the spectral range of 403 nm to 946 nm (the human visual range and into the near infrared), operating as a multispectral imager with up to 15 spectral bands. Up to 15 programmable spectral channels of image data with pixel sizes between 2 and 4 m can be acquired using an unpressurized aircraft. Borstad's CASI built in 1990 was upgraded in 1994 to improve its blue sensitivity for marine applications (Borstad, et al., 1997).

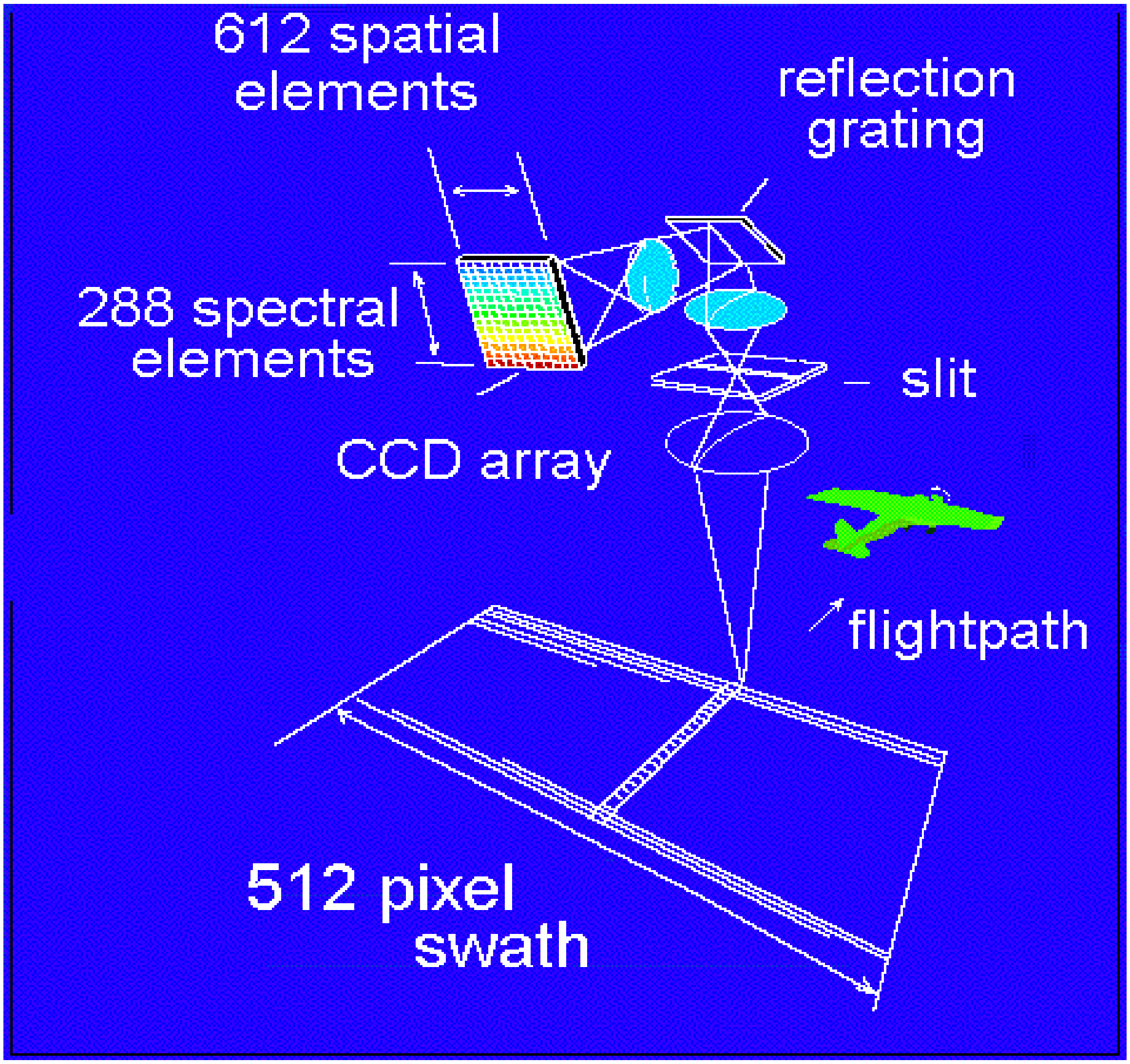

Fig. 5. CASI operating principle (used by permission of Borstad Associates).

CASI has been used in a number of marine projects to determine bottom type as well as marine habitats. One study by Borstad et al. (1997) for the Ministry of Fisheries and Marine Resources of the Republic of Mauritius shows an example of the ability to use this technology to classify coastal bottom types for hydrographic purposes (Figure 6). There is an abundance of geological applications for hyperspectral data on land, and Kruse et al. (1997) developed and applied these methods to nearshore hyperspectral ocean data. However, the main focus of this paper was in the realm of suspended sediments and biologic activity.

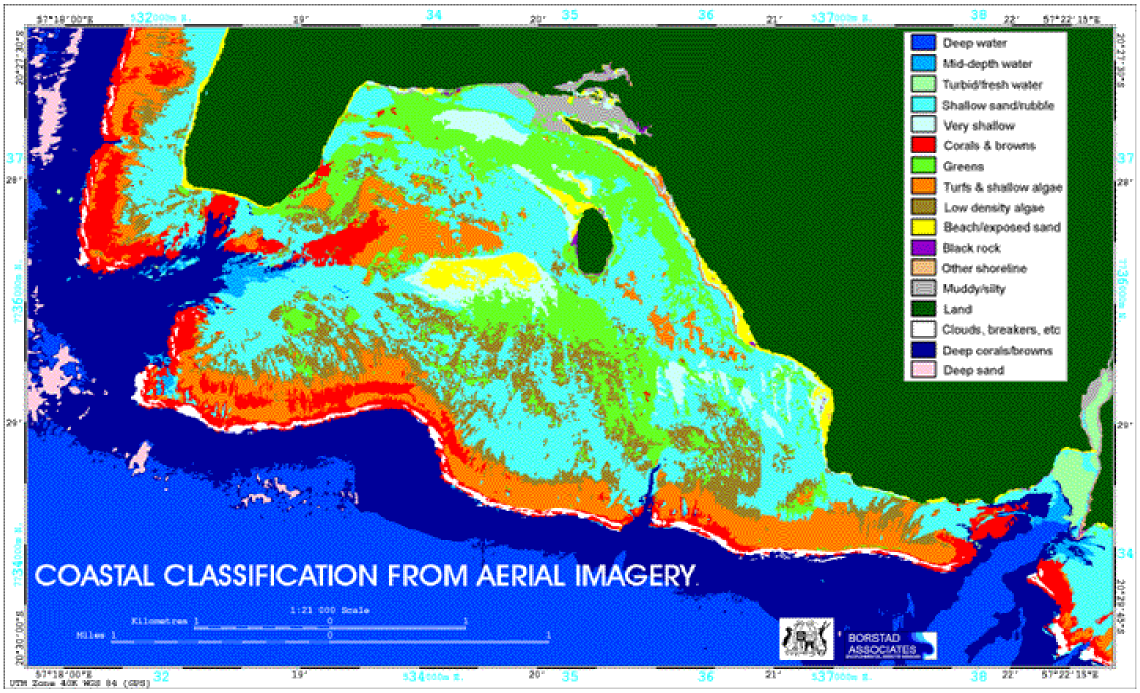

Fig. 6. Coastal Classification (used by permission of Borstad Associates).

SENSOR FUSION

No one sensor seems to be able to accomplish all of the goals of a hydrographic survey at the time of this writing (Table 3). Therefore, a combination of sensors needs to be explored to determine the best course for more complete cost effective hydrographic surveys by ALB.

Table 3. Existing technology capabilities for hydrographic surveys.

Measurements	ALB	Hyperspectral	Fathometer	Side-scan
bathymetry	X	limited	X	No
navigation hazards	X	X	X	X
bottom type	No	X	No	No
water optics	?	X	No	No

ALB systems have already been proven to give exceptional results in providing bathymetry where it can be used in a cost-effective manner. Based on spectral properties, CASI can provide information and detailed mapping of the distribution of nearshore sediments as well as marine and onshore vegetation. Combination of the two sensors can provide environmental data, greater depth resolution, and water optics (Estep et al., 1994). A fusion of SHOALS data and hyperspectral imagery allows the lidar depths to be used for calibration of the imagery. This means that the survey will be able to extract information on seafloor type, based on ground truth spectral signatures (Lillycrop and Estep, 1995). Given the current specifications for hydrographic standards and the necessity to characterize the environment more completely, the combination of these two sensors will put us a little further toward achieving that goal. Ground truth data, which includes field spectrometer readings of the different bottom types, will still be needed to accurately delineate the variations of bottom sediments by obtaining their in-situ spectral reflectances. This can be done after the airborne survey is complete and a bottom reflectance map is generated, which will be used to determine where field data spectral measurements need to be taken.

The Naval Oceanographic Office (NAVOCEANO) is partnered with the U.S. Army Corps of Engineers through a Memorandum of Agreement in the Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX). In addition to the availability of SHOALS survey services to NAVOCEANO, the partnership allows an exchange of ideas

and knowledge, particularly in the area of new development. One of the program goals of the JALBTCX is to explore the integration of other sensors with SHOALS on the aircraft for extended survey capabilities. Future missions for SHOALS and CASI to be flown together are being explored.

CONCLUSION

CASI is capable of accurately and cost-efficiently mapping bottom sediments and types in sufficiently clear water. Merged with the capabilities of SHOALS to determine depth accurately, a more complete hydrographic survey can be achieved more efficiently than traditional surveys. Increased understanding of the marine environment has led to the development of more-accurate models for a variety of measurements, including bottom reflectance and bathymetry (Terrie, 1995). This advancement is expected to increase as more people explore and take advantage of these advanced state-of-the-art sensors.

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